Raman Airborne Spectroscopic Lidar (RASL) – numerical simulations of water vapor performance

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RASL (Raman Airborne Spectroscopic Lidar)

- The Raman Lidar group at NASA/GSFC is developing an airborne Raman Lidar through the NASA Instrument Incubator Program (IIP)

- This system is being designed to be compatible with the NASA DC-8 and other similar aircraft

- It will be based on a 24" Dall-Kirkham telescope and a large pulse, tripled Nd:YAG laser (>15W @ 355 nm, ~50 Hz)

- The initial system design includes the following measurements:
  - Water vapor mixing ratio
  - Aerosol backscatter and extinction
  - Aerosol depolarization
  - Cloud liquid water

- Due to the great importance of water vapor in climate and weather studies, the anticipated water vapor performance of RASL has been carefully studied

The numerical model

- A Raman Lidar numerical model has been developed in Mathematica.
- Physical units are maintained throughout
  - Simulating actual data permits lidar optical efficiency and skylight intensity to be determined
- The lidar system overlap function is simulated analytically using both geometrical and optical functions
- Inputs required for the model:
  - telescope primary and secondary diameters, fov, F/#, telescope blur circle, telescope focus range, laser initial beam diameter and divergence, laser pulse energy, laser repetition rate, laser wavelength, Raman return wavelength, round trip attenuation, molecular number density profile, Raman cross section, zenith angle, averaging time, range resolution, spectral width of filter, filter transmission, PMT QE, PMT dark count rate
- The model has been extensively validated using ground-based data from two Raman Lidar systems

Overlap function simulations
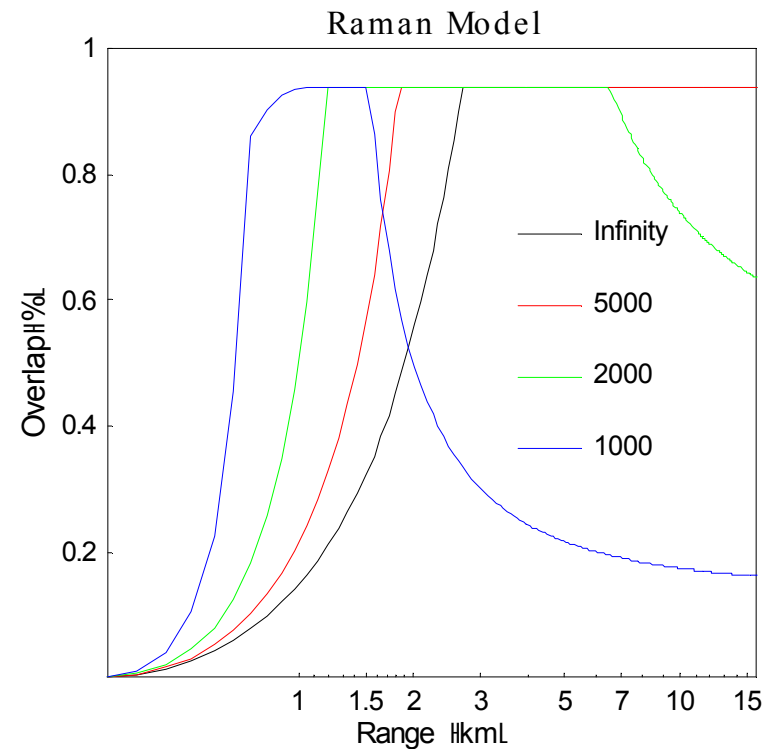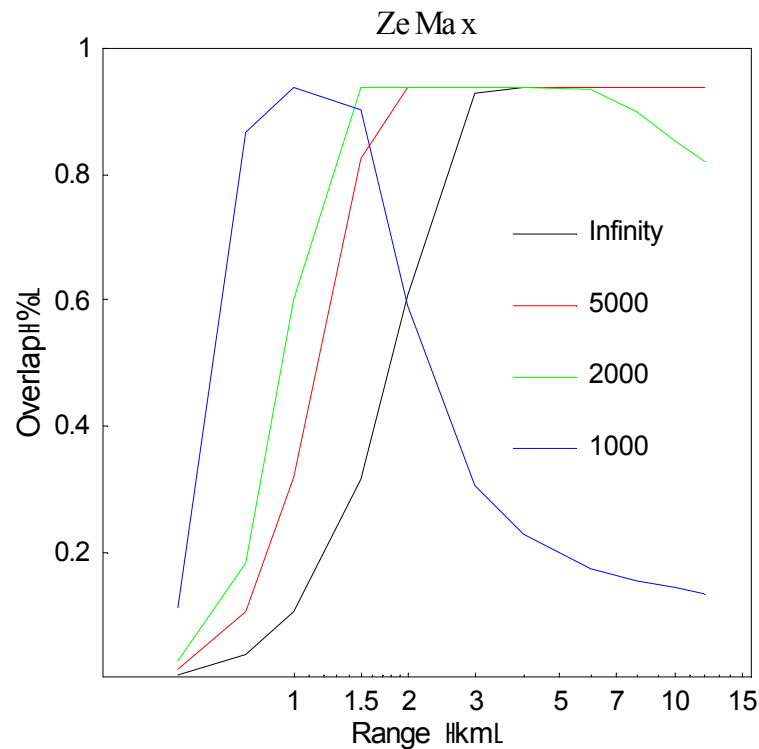
The overlap function for an F/4, 0.6 m telescope with 0.15 m secondary was simulated using both ZeMax and the numerical model. The laser beam diameter was 100 mm, with 60 urad divergence. FOV = 0.25 mrad.

Model tuning

- There are two free parameters that must be tuned for the model to match actual data
  - Lidar channel optical efficiency
  - Background skylight radiance
- The model was tuned to match data from two Raman lidar systems operated under quite different conditions
  - The NASA/GSFC Scanning Raman Lidar operating at night with 2 mrad fov.
  - The DOE CART Raman Lidar operating in the daytime with 0.27 mrad fov.

Tuning of model simulations of water vapor using SRL data – optical efficiency
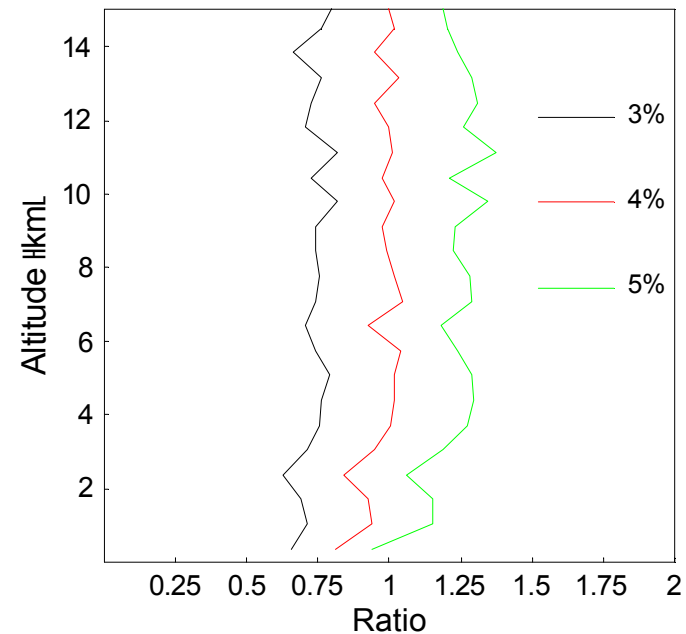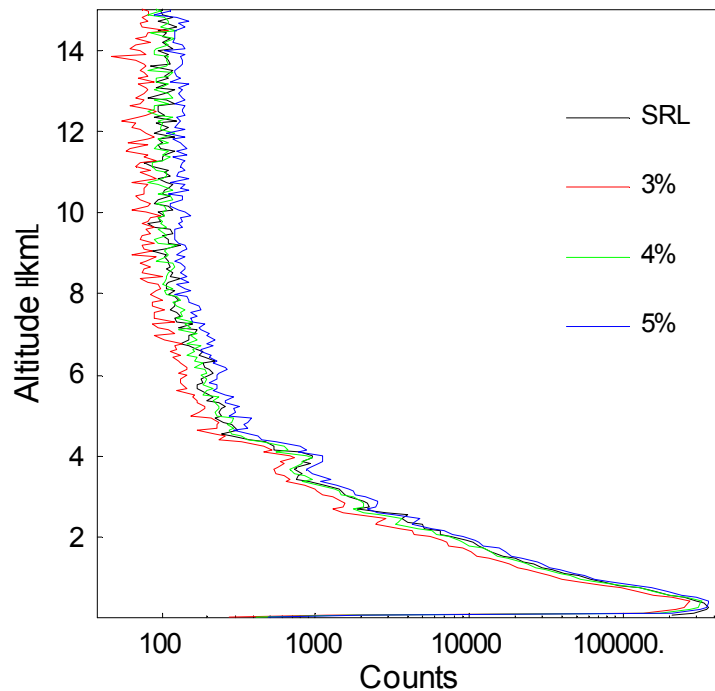

Using a 1 minute profile acquired at Andros Island, Bahamas on August 22, 1998, the model was tuned for water vapor channel optical efficiency and background skylight (next plot). On the right above, it can be seen that the optical efficiency offsets the curves throughout the profile and that 4% provides the best match.

# Tuning of model simulations of water vapor using SRL data – background skylight
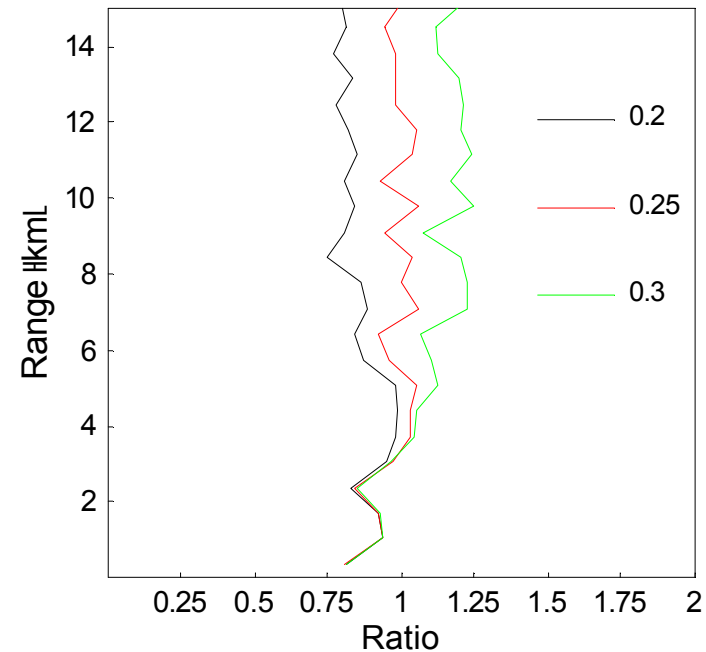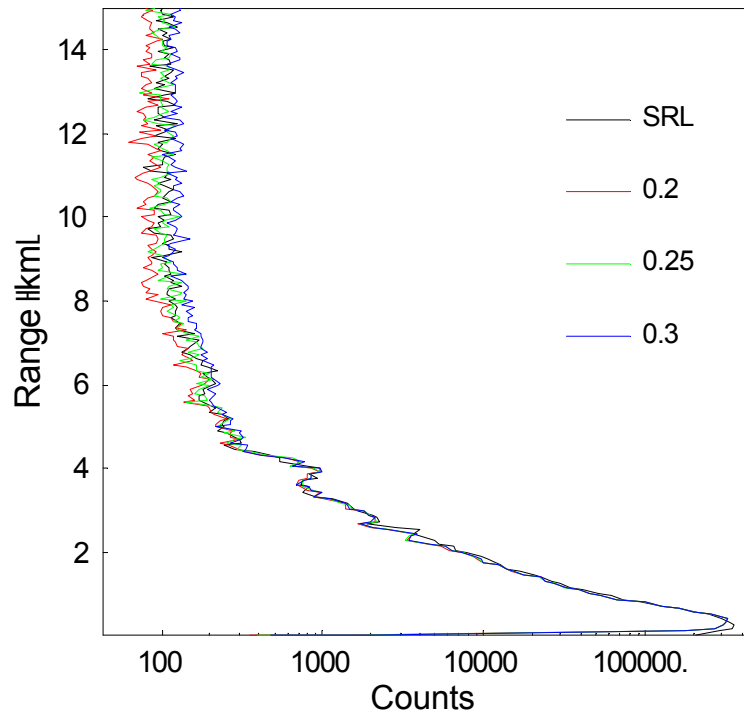
The background skylight – in units of 10^{-7} W/(cm^2 sr um) - is tuned so that the curves match in the upper portions of the profile. Note on the right that the background tuning mainly affects the curves above 4 km where the lidar return is less intense. This process must be done iteratively with the optical efficiency tuning

Model simulations of nitrogen and fully processed water vapor mixing ratio
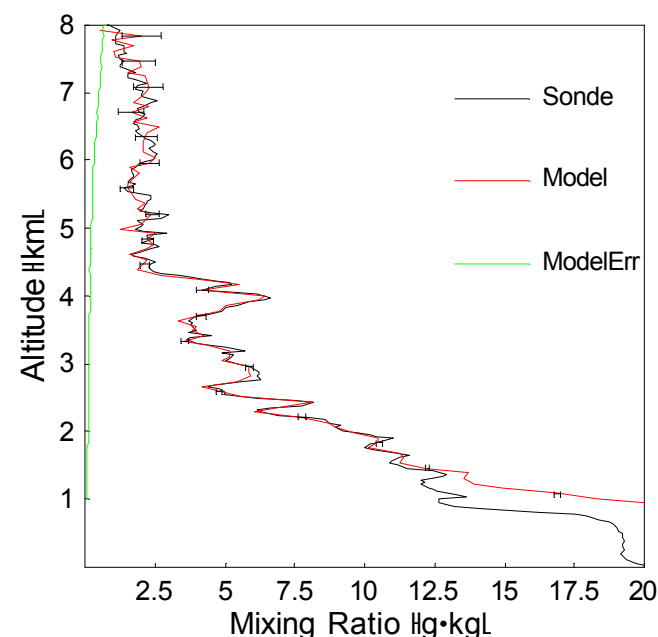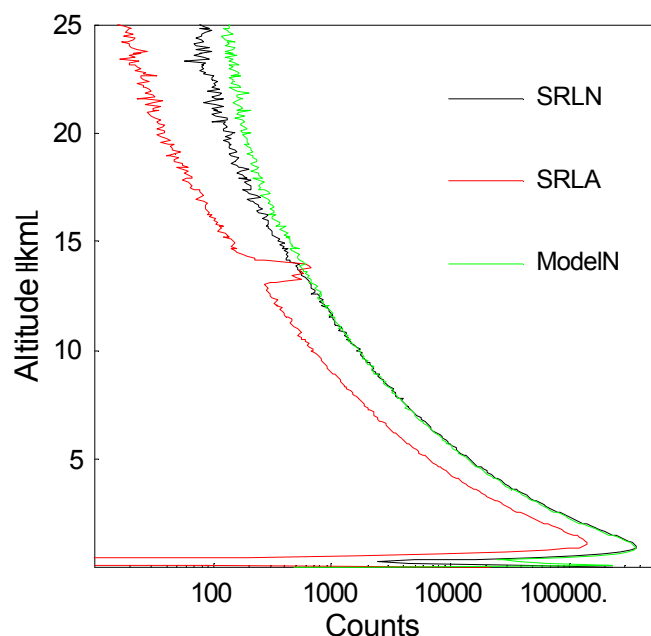
The same tuning procedure was followed for the SRL nitrogen data shown on the left (SRLN). Notice that the model did not know of the presence of a cirrus cloud at 13 km shown in the aerosol data (SRLA). On the right is shown the fully processed simulated water vapor mixing ratio versus a simultaneous radiosonde launch. Very good agreement is achieved. Only high channel data have been simulated here which explains the disagreement below ~2 km.

Model tuning using daytime CART Raman Lidar data
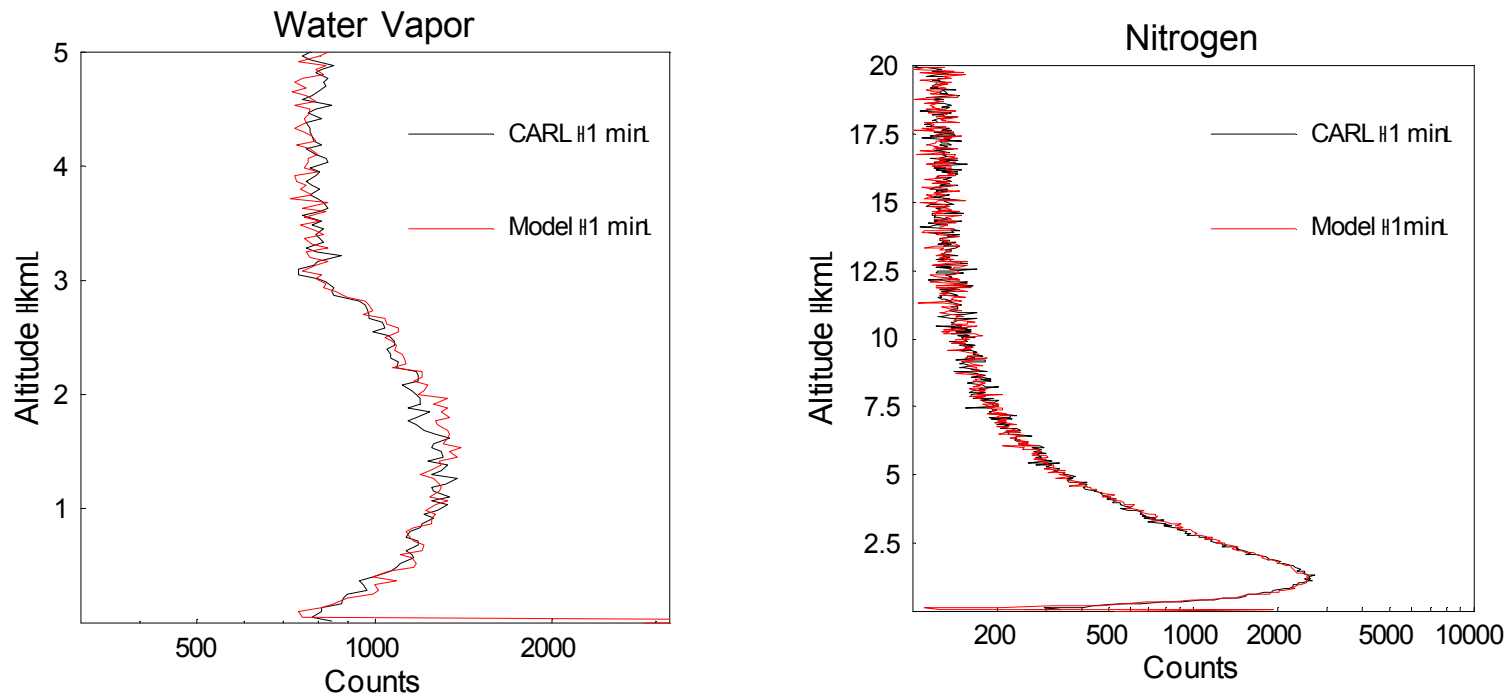
The same procedure was followed for daytime CARL profiles of water vapor and nitrogen. FOV=0.27 mrad. The background skylight needed to match the model agreed well with Modtran predictions for this case. Notice the reduced signal strengths versus SRL nighttime data due to ~ 10% and ~3% transmission filters used in the water vapor and nitrogen channels respectively to reduce the count-rates.

Fully processed water vapor mixing ratio – CARL simulation

- Fully processed 10 minute water vapor mixing ratio profile CARL vs model

- Below 2.5 km, the model disagrees with CARL due to small differences in overlap function simulations

- Signal to noise simulation of CARL is very good
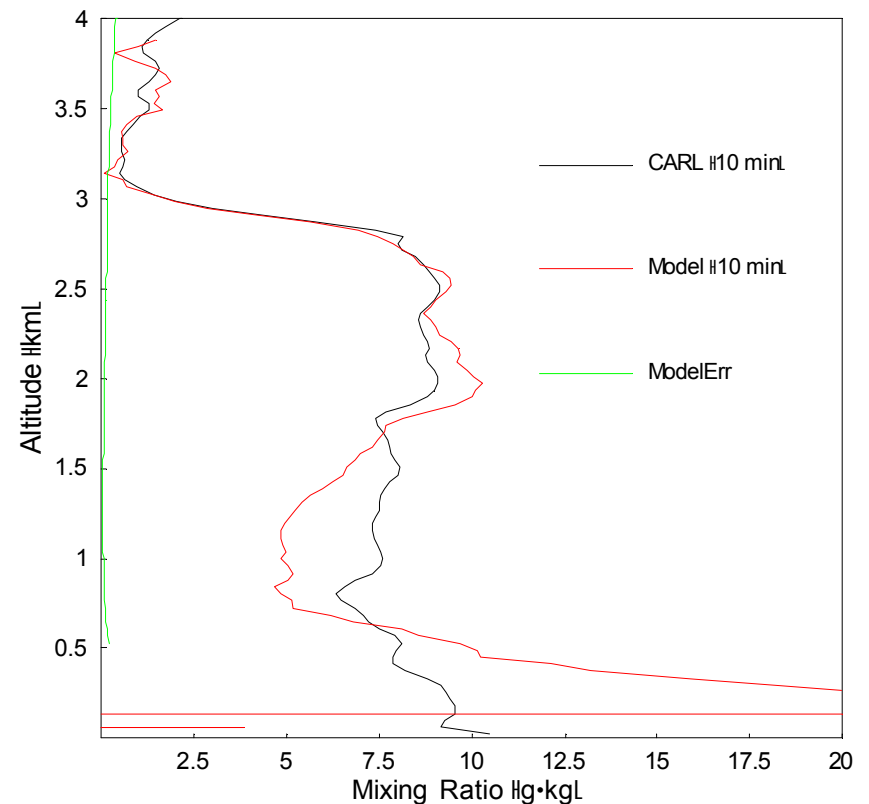
Airborne Simulations

- RASL performance for three cases, which span a range of water vapor conditions, will now be simulated
  - High water vapor: August 22, 1998 Andros Island, Bahamas
  - Medium water vapor: September 27, 1997 Oklahoma
  - Low water vapor: simulated arctic conditions in January

High water vapor – August 22, 1998
# Andros Island, Bahamas
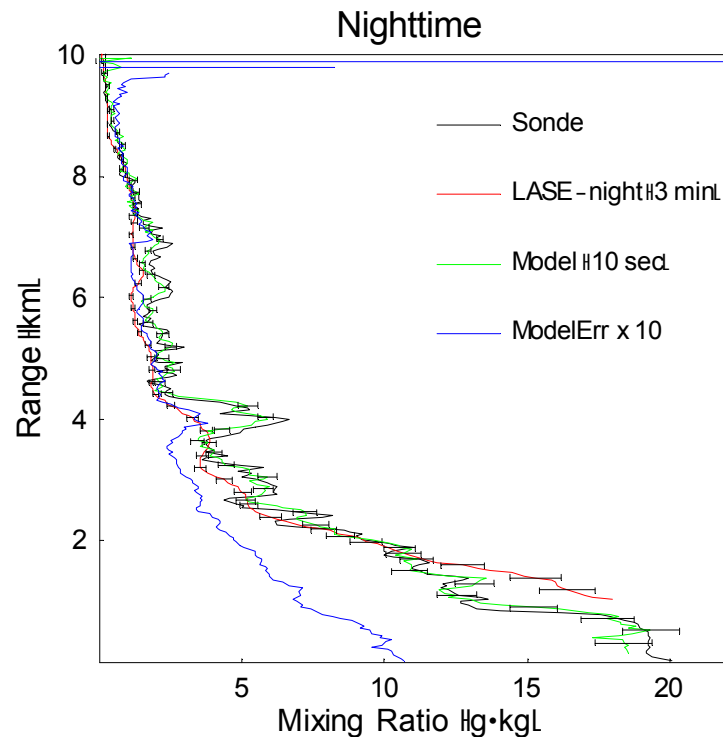
Nighttime simulations of RASL performance (10 sec) at Andros Island, Bahamas. Sonde and LASE (3 minute nighttime profile) are shown for comparison. LASE resolution is 0-2km: 330m, 2-6km: 510m, 6-8km: 990m. RASL resolution 0-5 km: 200m, 5-8km: 120m, 8-10km: 40m.
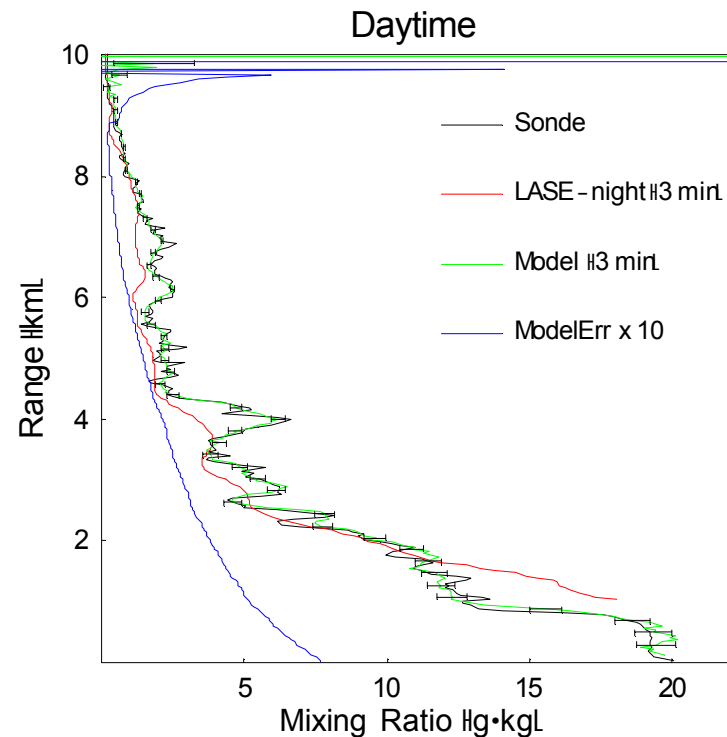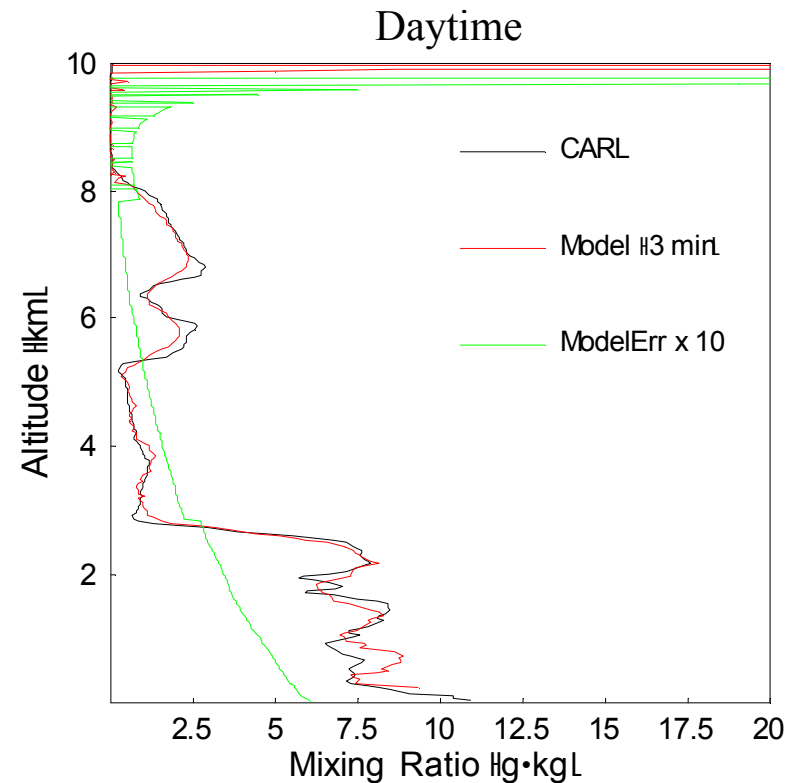
Daytime simulations of RASL performance (3 min) using 10^0 SZA over ocean background radiance and 3 minute average. Vertical resolution is now 200m from 0-9 km. LASE nighttime profile is the same as shown on the left.

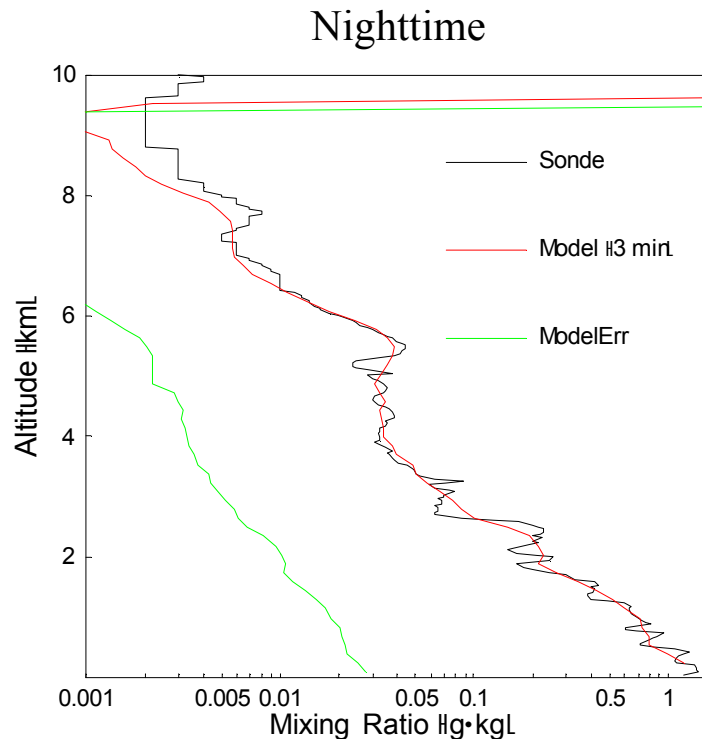# Medium water vapor – September, 1997 CART site
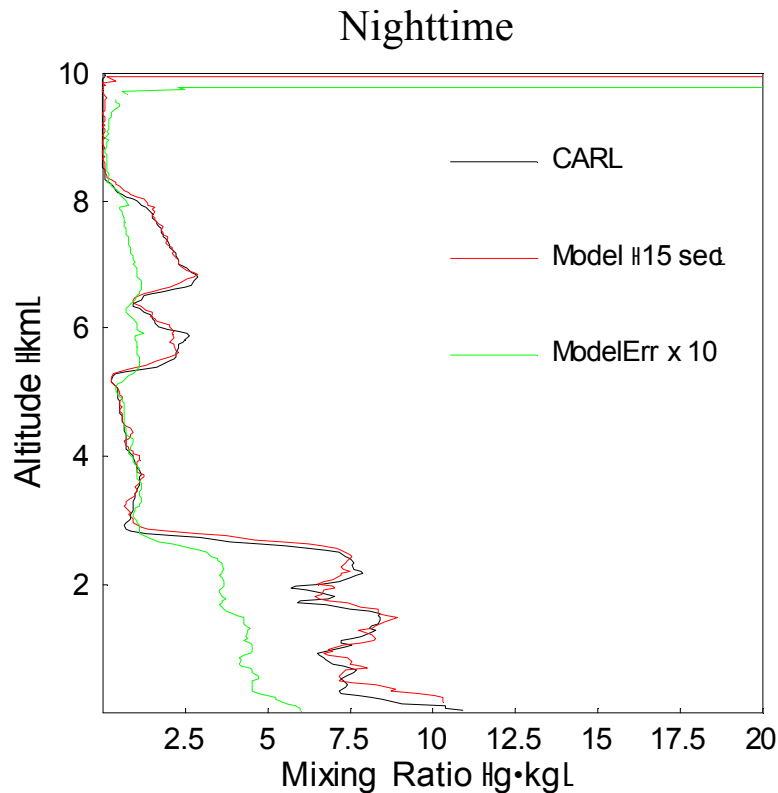
Nighttime results use 15 sec average. The nighttime resolution is 0-6 km: 200m, 6-8 km: 120m, >8 km: 40m.

Daytime results use 3 minute average. Resolution is 0-3 km: 350m, 3-8 km: 520 m, >8 km: 40 m. The background light was for 30º SZA over grass: 1.3 W/(cm² sr um)

Low water vapor – simulated arctic conditions in January

Nighttime

Daytime

The upper portion of the August 22, 1998 radiosonde profile was used to simulate arctic conditions. Nighttime RASL performance is shown using 3 minutes of data acquisition. Resolution is 0-5km: 750m, 5-9km: 450m. Random error is less than 5% at the surface.
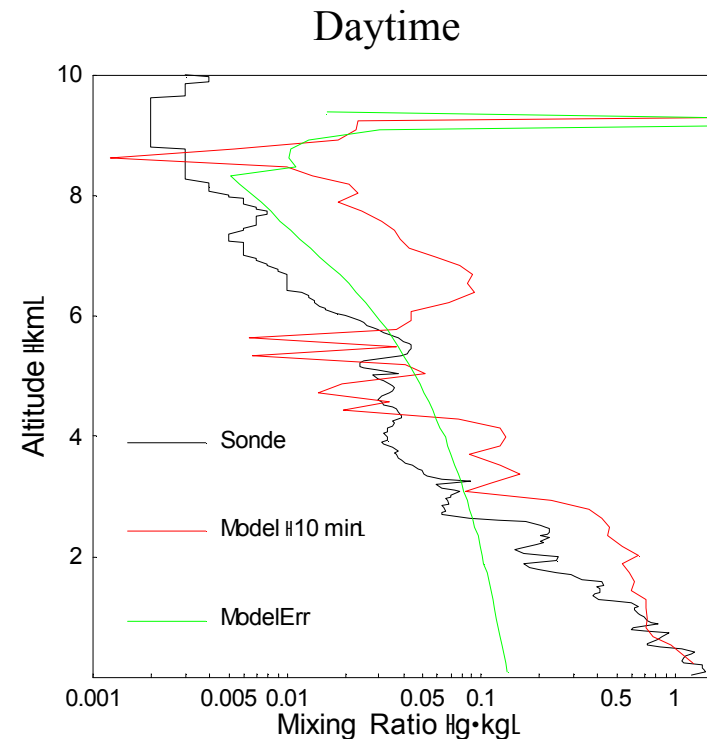
Daytime RASL performance is shown using 10 minutes of data acquisition. Resolution is 0-9km: 1050m. Under such conditions, a DIAL lidar could have an advantage by tuning to a stronger absorption line. Background radiance used was for 40º SZA over snow.

Airborne Raman Lidar - Advantages

- There are several factors that make an airborne Raman lidar attractive versus the same system on the ground
  - There is a distinct range compression that occurs from an airborne platform
  - Under many circumstances, the background radiance is lower
  - Eye safety standards are much easier to meet with a UV laser (355 nm simulated here)

Dynamic range compression looking downward

- The simulated raw water vapor signal (black) shows less than 1 decade variation in the signal between the surface and 8 km. The nitrogen signal (red) also shows about 1 order of magnitude variation.

- The dynamic range compression is by several orders of magnitude when compared with the ground-based data shown earlier. This improves S/N versus range and allows detectors to operate more linearly.
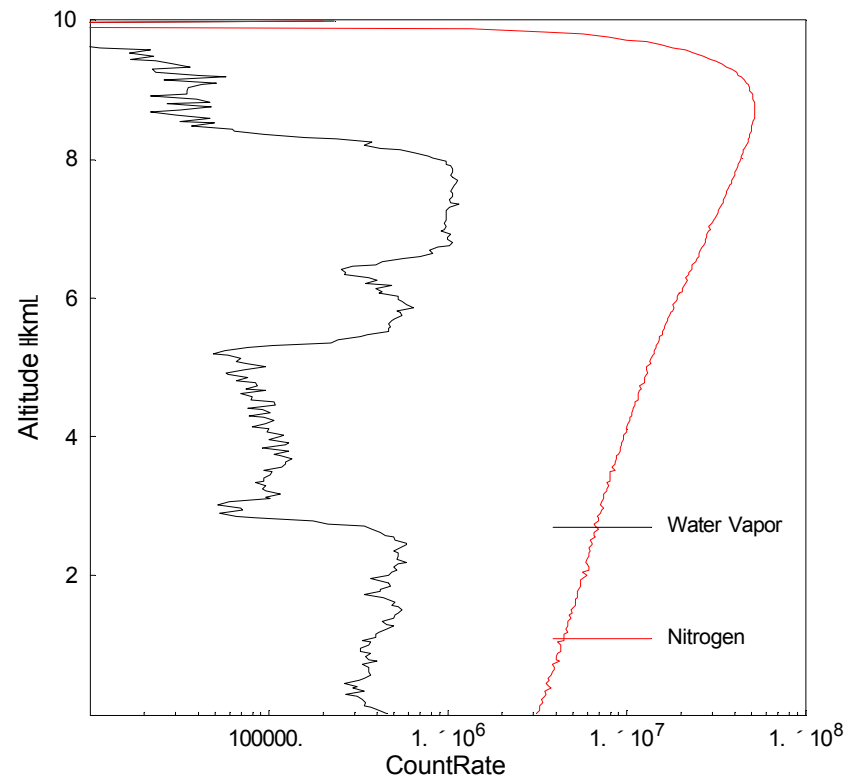
Downward-looking Background Radiance

- The radiance required by the model to match the up-looking CARL data for 38^0 SZA in Oklahoma was 1.5×10^{-2} W/(cm^2 sr um)

- This equals or exceeds the radiance for any SZA over either water or grass surfaces as predicted by Modtran V3.7
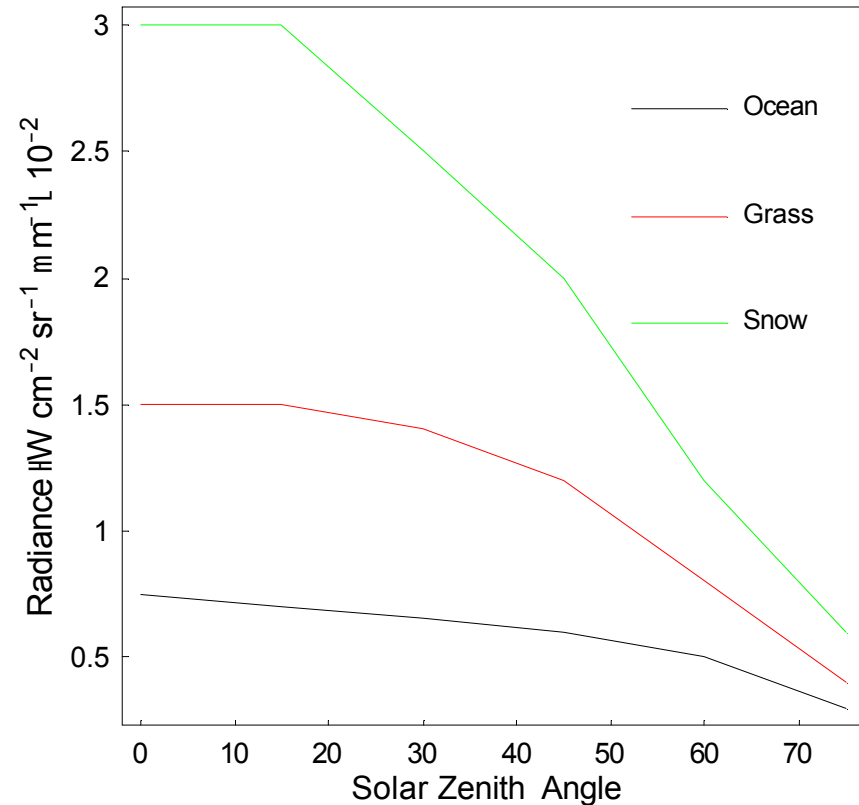
A UV system is greatly preferred for eye-safety

- A UV laser source such as the tripled Nd:YAG is substantially more eye-safe than the laser for a DIAL system operating in the near IR.

- Currently, the highest power commercially available Nd:YAG laser offers ~ 15-20 W with 0.35 J pulses (Continuum 9050). Such a system is eye-safe a few hundred meters below the plane (green)

- A 815 nm, 0.1 J laser, such as used in LASE, is not eye-safe until approximately 8 km below the plane (blue)

- A 50 J 355 nm laser pulse poses approximately the same eye hazard as a 0.1 J, 815 nm pulse (purple)

- *Higher power Nd:YAGs will not present eye-safety problems when they become available.*

Laser Energy Density Looking Down From 10 km
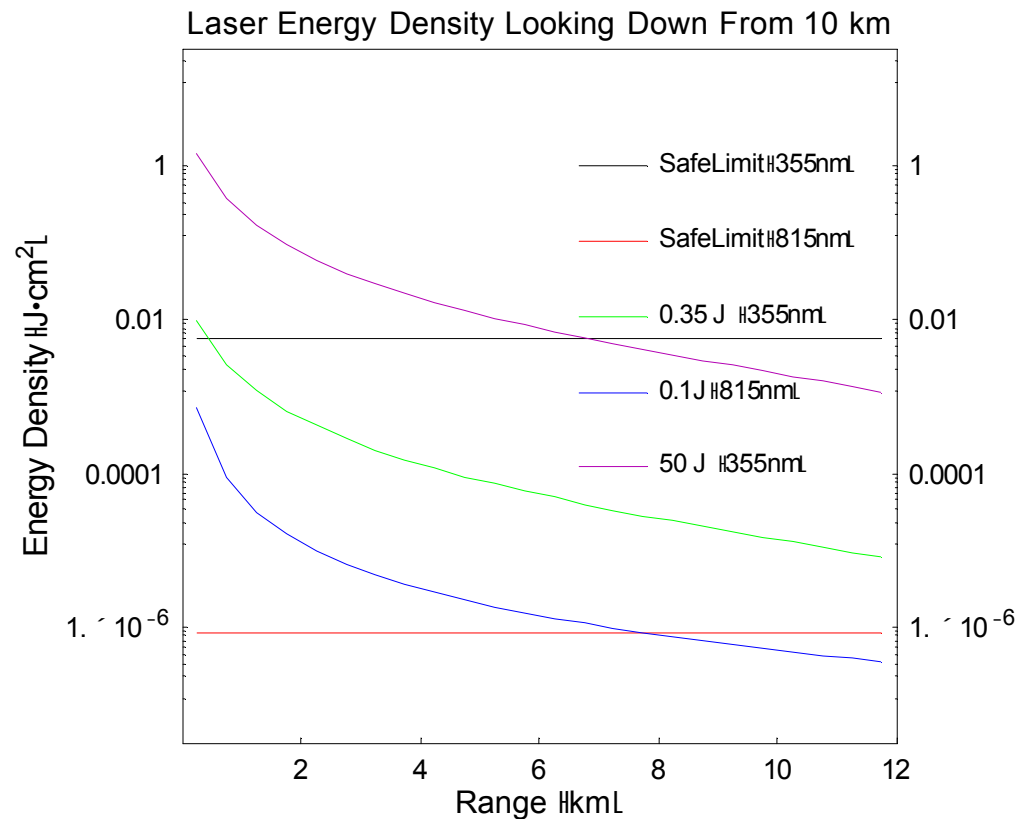
Summary and Conclusions

- Numerical simulations of the Raman Airborne Spectroscopic Lidar (RASL) have been performed for a range of water vapor conditions

- Dynamic range compression and reduced background radiance implies reduced acquisition times from an airborne platform
  - High quality profiles of water vapor are available under most conditions in as little as 10 seconds at night and typically 3 minutes during the day

- Much higher pulse energies can be used than are currently available commercially and still remain eye-safe. By contrast, the much lower eye safety limits in the near-IR will require DIAL systems operating in that region to increase their repetition rate in order to improve their measurements and still remain eye-safe.

RASL Preliminary Layout